Exploring integrated crop–livestock systems in different ecoregions ofthe United States

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Exploring integrated crop–livestock systems in different ecoregions of the United States

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ABSTRACT

Large-scale, energy-intensive, specialized production systems have dominated agricultural production in the United States for the past half-century. Although highly productive and economically successful, there is increasing concern with unintended negative environmental impacts of current agricultural systems. Production systems integrating crops and livestock have potential for providing additional ecosystem services from agriculture by capturing positive ecological interactions and avoiding negative environmental outcomes, while sustaining profitability. A diversity of ecologically sound integrated crop-livestock systems have been and can be employed in different ecoregions: sod-based crop rotations, grazing cover crops in cash-crop rotations, crop residue grazing, sod intercropping, dual-purpose cereal crops, and agroforestry/silvopasture. Improved technologies in conservation tillage, weed control, fertilization, fencing, and planting, as well as improved plant genetics offer opportunities to facilitate successful adoption of integrated systems. This paper explores the use and potential of integrated crop-livestock systems in achieving environmental stewardship and maintaining profitability under a diversity of ecological conditions in the United States.

1. Introduction

Agriculture in the U.S. has undergone tremendous change in the past century. Before World War II, U.S. agriculture was labor intensive and characterized by many small, diversified farms (Dimitri et al., 2005; Rotz et al., 2005). Farm products were distributed primarily in local markets. Nutrients for crop growth were cycled within and among local farms, primarily via manure, so crop and livestock production were closely linked. Crop residues and non-cultivated land were used to support production of meat, milk, and associated products, and livestock manure improved the quality and fertility of cultivated soils (Russelle et al., 2007). Since that time, production in the U.S. has become increasingly concentrated in large-scale, energy-intensive farms to meet domestic and international market demands (Hoppe et al., 2007; Russelle and Franzluebbers, 2007). Large family and non-family farms now account for 10% of all U.S. farms but more than 75% of agricultural sales; in 2007, the largest 2% of farms were responsible for 59% of total farm sales (NRC, 2010).

Specialization in agricultural systems has resulted in decoupling of crop and livestock production (Ray and Schaffer, 2005), disrupting within-farm nutrient cycling leading to large nutrient imbalances; excessive nutrient accumulation occurs on large confined animal feeding operations, while grain farms rely heavily on purchased fertilizers (Chang and Entz, 1996). Some discussion of integrating livestock with ethanol production has occurred, but most scenarios involve feeding byproducts from ethanol plants (distiller's grains) to livestock in concentrated animal-feeding operations. Since ethanol production from corn grain may not be sustainable in the long-term, a search for alternative biofuel feedstock has already begun. Forages grown for biofuel production could eventually play a role in expanding integrated crop-livestock systems in the U.S.

Reasons for specialization in agriculture in the U.S. are numerous, resulting in interdependent socio-economic relationships at local, regional, and national levels (NRC, 2010). Just to summarize this broad and complex topic, specialized systems were developed to (i) meet increasing market demands for raw commodities and specific food-industry standards in an increasingly processed food delivery system, (ii) capture economies of scale with greater availability and low cost of fossil-fuel-derived inputs, (iii) take advantage of advanced machinery developments on and off the farm, (iv) conform to government incentives to create and expand

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export markets, and (v) avoid the risk of weather disasters, market assurances, and social pressures that could lead to volatile and poor marginal costs of production otherwise (Ikerd, 2009; Kirschenmann, 2009; Steiner and Franzluebbers, 2009).

Although agriculture in the U.S. has been economically successful with dramatic growth in farm output, current agricultural systems have contributed to a number of unintended negative environmental consequences (Russelle and Franzluebbers, 2007), including impairments of water quality, reduced groundwater supplies, depletion of soil organic matter, and excessive soil erosion. Sedimentation of reservoirs and eutrophication of surface and marine waters remain major societal issues (Karlen et al., 1994; McIssac et al., 2001). In addition, short rotations with low crop diversity have led to increasing insect problems, such as infestation of soybean cyst nematode (*Heterodera glycines* Ichinohe) where soybean [*Glycine max* (L.) Merr.] is grown frequently (Porter et al., 2001). Adaptations of insect pests have also occurred under short rotations. A good example is development of extended diapause of the western corn root worm (*Diabrotica virgifera virgifera* LeConte), enabling the pest to delay egg hatching for one year when a non-host crop is grown (Levine and Sadeghi, 1991). Other problems encountered with specialized systems of low crop diversity are herbicide-resistant weed populations (Culpepper et al., 2006; Derksen et al., 2002; Trainer et al., 2005) and greater incidence of crop diseases (Lipps et al., 1996). As well, specialized agricultural systems have vastly altered energy and nutrient cycles compared with those occurring in natural or mature ecosystems, thereby impairing the stability and resiliency of agricultural landscapes (Gates, 2003).

A growing number of scientists and innovative producers in the U.S. have been exploring ways to improve environmental sustainability of agricultural systems by integrating of crop and livestock enterprises to foster greater biodiversity through use of perennial and annual forage species that not only provide livestock feed but can be used to achieve multiple environmental benefits (Russelle et al., 2007). Greater biological and enterprise diversity found in integrated systems can result in more efficient nutrient cycling than in specialized production systems, such that nutrients in forage crops consumed by livestock are applied back on the land through manure deposition, which in turn enhances soil tilth, fertility, and carbon (C) sequestration (Russelle et al., 2007). Our objective here is to describe cases of recent integrated crop-livestock systems being practiced in the U.S. and highlight research supporting the development of viable integrated crop-livestock production systems for the future.

2. Integrated crop-livestock systems in the U.S.

The U.S. is a geographically diverse country, which can be divided into various well-known geopolitical regions (Fig. 1) having large climatic differences (Fig. 2). Crop production under rain fed conditions predominates in the humid regions of the Northeast, Midwest, Southeast, and upper Pacific Northwest. Irrigation is often needed in the western dry regions of the Great Plains, Rocky Mountains, and California. Although integrated crop-livestock systems are not widely practiced in any region of the country, there are opportunities to adopt a variety of these practices in many regions, as discussed further in this paper. Various incentives and regulations interacting with local and regional natural resource concerns determine whether technical, economic, sociological, or political issues will predominate in such change.

Integration of crop and livestock farming can and do occur at two practical scales in the U.S: (i) within a farm, where spatial and temporal integration occurs on the same land base and (ii) among farms, or regional integration, in which spatially separated crop and livestock farms work together through verbal agreements or written contracts to achieve synergies between crop and livestock production systems (Entz et al., 2005; Russelle et al., 2007; Steinfeld, 1998). Both scales of integration are dynamic and offer advantages and challenges, both require a high degree of management skill, and both are practiced and are worthy of scientific exploration (Entz et al., 2005; Russelle et al., 2007).

The most commonly researched and practiced methods of crop-livestock integration in the U.S. are (i) sod-based crop rotations, (ii) livestock grazing of cover crops within cash-crop rotations, (iii) grazing of crop residues, (iv) sod intercropping, (v) dual-purpose cereal crops, and (vi) agroforestry and/or silvopasture. We focus on these six methods, because they are the most commonly practiced. Other forms of crop-livestock integration are occasionally practiced in the U.S., such as small-scale confined livestock fed conserved forages and crop residues with manure spread back on smaller parcels to build fertility organically, grain-fish pond-animal manure systems, slurry-pond irrigation of pastures and crops, crop-farm and livestock-farm trading of products and by-products, cash-rental by livestock producers of grain stubble fields or cover crops, and land application of various organic "wastes" whether agricultural or industrial.

2.1. Sod-based crop rotations

Sod-based crop rotations typically involve 2–10 years of perennial forages (i.e. sod) rotated with 1–8 years of cropping. This approach was common in many regions of early-American agriculture (USDA-NRCS, 2004). Benefits of using extended periods of perennial pasture/hay in rotation with cash crops (i.e. sod-based crop rotations) have been well recognized and documented across all regions of the U.S. (Franzluebbers, 2007; Russelle et al., 2007; Sulc and Tracy, 2007). Benefits include: (i) reduction of nitrogen (N) losses, especially less nitrate leaching, (ii) reduced soil erosion, (iii) increased soil organic C and associated improvement in soil structure, water holding capacity, nutrient supply, and higher crop yield potential, (iv) reduced fertilizer N requirements for succeeding non-legume crops, thereby reducing input costs, energy demands, and environmental impacts of farming, and (v) improved yield from reduced insect, disease, and weed pressures. Integrating livestock into sod-based crop rotations reduces feed costs, improves profitability, and increases soil C accumulation and sequestration with manure recycling. Greater crop yields have been reported for up to five years following termination of sod crops in the warm, humid region (Fig. 2) (Franzluebbers, 2007). Managing cropland with no-tillage after termination of a perennial pasture phase preserved the positive soil quality benefits achieved during the pasture phase, thereby enhancing production and environmental outcomes (Franzluebbers and Stuedemann, 2008a,b). Similar results were found in the cool, dry region (Fig. 2) where near-surface soil properties representative of key soil functions were not adversely affected during nine years following conversion of perennial grassland to an integrated crop-livestock rotation with winter grazing of cattle (Liebig et al., 2011a). These findings in two contrasting climatic regions are significant in that they demonstrated methods of converting perennial grassland to diverse annual cropping plus livestock grazing without adversely affecting the soil environment.

Despite many documented benefits, the practice of rotating cash crops with perennial forages/pastures is limited across much of the primary U.S. crop producing regions. Pastures are most commonly established on land not particularly suitable for cash crops. Even if land were acceptable for no-till cash-crop production, producers are averse to terminating perennial pastures that may have been expensive to establish and took a couple years to reach full potential. Short-term (two to three years) pasture rotated with crops

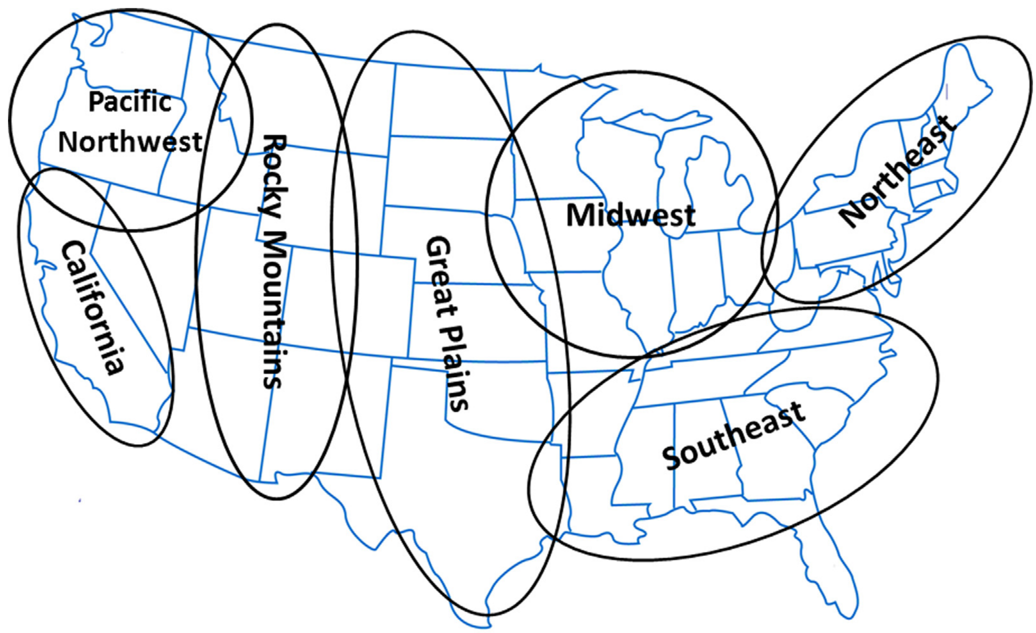

Fig. 1. Major growing regions of the U.S. based on climate (temperature and precipitation), landscape, and agricultural production characteristics.

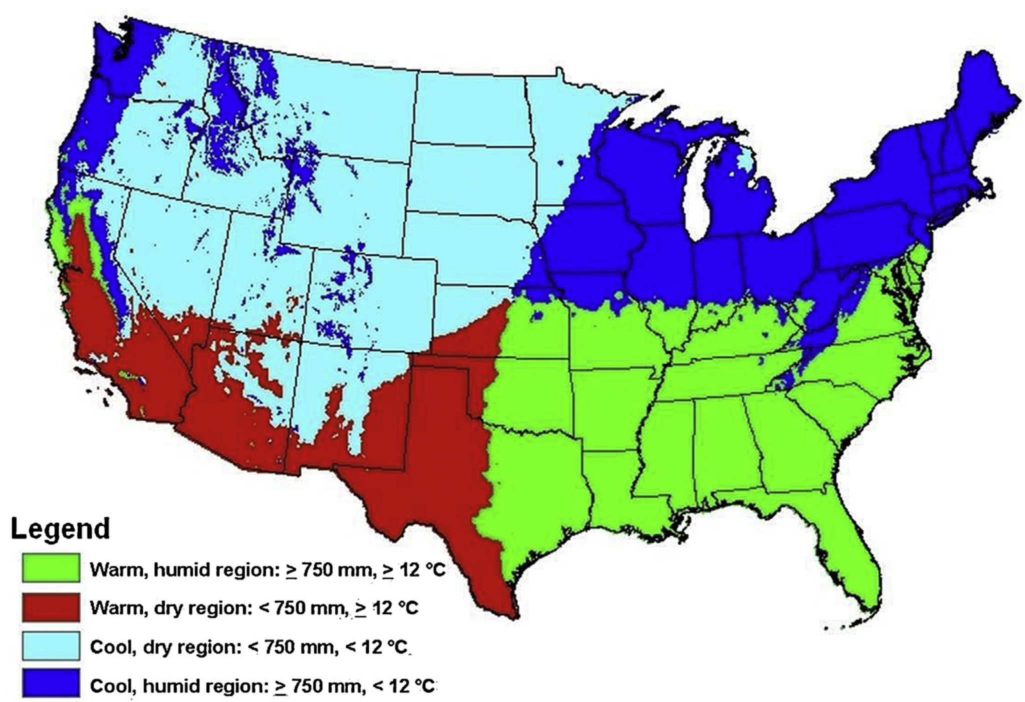

Fig. 2. Major climatic divisions in the U.S. based on mean annual temperature (cool, <12 °C; warm, >12 °C) and mean annual precipitation (dry, <750 mm; humid, ≥ 750 mm). Produced by H.J. Causarano using the Spatial Climate Analysis Service (www.ocs.orst.edu/prism/), and published by Franzluebbers (2007).

is also rare, a result of many incentives toward specialization and large-scale agricultural production, but some exceptions exist.

One sod-based crop rotation that has not lost favor is corn (*Zea mays* L.) with alfalfa (*Medicago sativa* L.) or alfalfa-grass mixtures on dairy farms, in which forage is mechanically harvested for three to four years and then rotated with corn. Forage is fed to dairy cows and nutrients are cycled back to the land via application of manure. This is an example of spatially separated crop-livestock integration on the same farm.

Producers in the southeastern U.S. have experimented with a sod-based rotation of two years of bahiagrass (*Paspalum notatum* Fluegge) or bermudagrass [*Cynodon dactylon* (L.) Pers.], followed by one year of peanut (*Arachis hypogaea* L.), and then one year of cotton (*Gossypium hirsutum* L.). Researchers and extension specialists in the region have been conservatively optimistic that adoption of this system will continue to expand (D. Hancock and D. Wright, personal communication, 2012) as producers become aware of its many benefits demonstrated through research (Hartzog and Balkcom, 2003; Katsvairo et al., 2006, 2007). Producers are interested in the system as a means to overcome stagnant cash-crop yields, disease and nematode problems, and the risk of cash-crop damage from late-season hurricanes common in the region. During the pasture phase, some producers have oversown the perennial bahiagrass or bermudagrass sods with cool-season annuals, such as annual ryegrass (*Lolium multiflorum* Lam.), to increase forage productivity with additional grazing days in early winter and spring before bahiagrass resumes active summer growth. When bahiagrass sod is terminated at the end of its second year, oat (*Avena sativa* L.) and winter rye (*Secale cereale* L.) have been seeded and grazed by livestock through winter and early spring prior to planting cotton or peanut. Oat and winter rye have also been sown each autumn after cotton and peanut harvest and grazed during the winter and early spring. In this way, grazing has occurred each winter within the sod-peanut-cotton rotation. Some producers have also been experimenting with annual cool-season legume cover crops within the system to provide N to the following cotton crop.

Marois et al. (2002) used an economic model to compare a conventional cotton (53 ha) and peanut (27 ha) rotation with a sod-based rotation system (20 ha cotton, 20 ha peanut, 40 ha bahiagrass) on a typical small farm in Florida. Net profit on the conventional farm was estimated as \$15,689 year^{-1} increasing to \$35,552 year^{-1} on the pasture-based farm with hay harvest only and to \$44,840 year^{-1} on the pasture-based farm with cattle grazing second-year bahiagrass.

Effects of perennial grass pastures on cotton and peanut production and soil quality responses were investigated near Suffolk Virginia (Faircloth et al., 2007; Weeks et al., 2007). Cotton grown after perennial grass was more vigorous and resulted in greater lint yield than following other row crops. Producers in the area were interested in modifying rotations based on those encouraging results.

The research and examples of farming systems described above demonstrate the tremendous potential of more diverse and ecologically sound sod-based crop rotations that concurrently achieve environmental conservation and production goals. Sod-based rotations can be successfully adopted by farmers in any region of the U.S. that incorporate either annual forages or long or short periods of perennial crops with grain crops. Such rotations will function most efficiently when livestock are integrated into the farming system to utilize the forage and crop residues and enhance nutrient cycling within the system.

2.2. Cover crops for forage

Cover crops are defined in the U.S. as plants established for the purpose of temporary or seasonal soil cover. They have long been promoted for achieving soil conservation, soil improvement, weed control, and nutrient cycling. Such benefits are usually perceived as indirect in terms of improving economic viability of cropping systems. Many of the species promoted and utilized as cover crops can serve as excellent sources of forage for livestock grazing, and therefore, should be considered more directly for overall system profitability (Franzluebbers, 2007; Sulc and Tracy, 2007). Additionally, grazing of winter cover crops can lower winter feed costs, as well as being less susceptible to unfavorable weather conditions compared with mechanical forage harvesting (Lawrence and Strohbehn, 1999). However, many crop producers have concerns that cattle trampling will adversely affect soil physical properties and subsequent crop productivity. Research has addressed this concern and will be highlighted in the following sections describing cover crop use across the country.

Incorporating winter cover crops into cropping systems is not easy in all ecoregions of the U.S. For example, success in utilizing winter cover crops becomes more variable to the north (colder with fewer growing degree days) and west (drier) (Strock et al., 2004). Nevertheless, opportunities exist for incorporating winter cover crops or short-season forage crops within cropping systems in nearly all ecoregions of the U.S.

2.2.1. Cover crops as forage in the southeastern U.S.

Cover crops provide a viable short-rotation opportunity for almost any cropping sequence in the warm, humid southeastern region (Fig. 2); this is the most favorable environment for growing winter cover crops in the U.S. In this region, winter cover crops can be grown for cut forage or grazing after summer cash crops, such as corn, grain sorghum [*Sorghum bicolor* (L.) Moench], cotton, peanut, or soybean. The most commonly grown winter cover crops in the region are annual ryegrass, winter rye, wheat, and crimson clover (*Trifolium incarnatum* L.). Winter cover crops are most often grown for conservation cover with chemical termination prior to cash-crop planting, as well as sometimes harvested as haylage or grazed by livestock. Summer annual forage cover crops can also be grown after winter cash crops, such as winter wheat (*Triticum aestivum* L.).

Several studies have been conducted in the southeastern region to evaluate cover crop grazing by livestock as a means to achieve both production and soil conservation goals. In a multi-year experiment on an eroded sandy clay loam soil in the Piedmont of Georgia, long-term pasture was converted to cash cropping with cover crops that were either grazed by cow-calf pairs (2430 kg live animal ha^{-1} for 47 days) or left ungrazed strictly for conservation purposes (Franzluebbers and Stuedemann, 2008a,b). Cover crop production was consistently greater with no tillage than with conventional tillage, which when grazed supported greater cattle gains with no tillage (330 kg ha^{-1} season^{-1}) than with conventional tillage (240 kg ha^{-1} season^{-1}). Soil compaction and degradation due to cattle traffic was not observed. During the first three years, stability of soil aggregation (0–6 cm depth) was similar whether cover crops were grazed or not (Franzluebbers and Stuedemann, 2008b). Frequent cultivation alleviated surface compaction in the conventional tillage treatment, while high surface soil organic matter resisted the forces of cattle traffic in the no-tillage treatment. Using conservation tillage with cover crop grazing helped avoid soil organic matter decline and nutrient cycling deterioration associated with sod destruction in order to produce a cash crop. In southern Georgia and Alabama, stocker cattle grazing of winter cover crops produced variable responses in subsequent cotton and peanut yield and soil properties; being both unaffected and negatively affected in different evaluations (Hill et al., 2004; Siri-Prieto et al., 2007a,b). Authors concluded that additional cattle gain of 178–561 kg ha^{-1} obtained from cover crop grazing increased income and justified diversification.

While cover crops can provide high-quality forage in short rotations as part of an integrated crop-livestock system, such use does not nullify their potential to also contribute to soil organic matter accumulation. In reviewing soil organic C changes with agricultural management in the southeastern U.S., Franzluebbers (2010) noted cover crops increased soil organic C sequestration by 83% in no-tillage systems (550 ± 60 kg ha^{-1} yr^{-1} with cover crops vs. 300 ± 50 kg ha^{-1} yr^{-1} without cover crops). On a sandy loam in Georgia, surface residue N plus total soil N (0 to 6 cm depth) was not affected whether cover crops were grazed or not during the first three years of crop-livestock integration (700 vs. 730 kg ha^{-1} with conventional tillage; 1670 vs. 1720 kg ha^{-1} with no tillage) (Franzluebbers and Stuedemann, 2008a).

2.2.2. Cover crops as forage in dry regions

Cover crop use in the cool, dry and warm, dry regions of the U.S. (Fig. 2) is most limited by moisture availability, but opportunities exist for cover crops to play a role in integrated crop-livestock systems. For example in Texas, an integrated system was evaluated having winter rye grazing in rotation with cotton to complement permanent warm-season grass pasture for steers. In that system, warm-season grass was grazed by steers intermittently through the year, while rye winter cover crop and dormant warm-season pasture were grazed from January to mid-April. When compared with conventional cotton monoculture, the integrated system reduced irrigation water use by 25% and N fertilizer use by 36%, and improved various soil quality properties, while remaining economically competitive (Acosta-Martinez et al., 2004, 2010; Allen et al., 2007, 2012).

A new option for cover cropping in the southern Great Plains is growing short-duration pigeonpea (*Cajanus cajan* L. Millsp.) as a leguminous cover crop after winter wheat to supply forage during the summer when native perennial grasses lack sufficient quality for cattle. Advantages of pigeonpea include using water and nutrients below the effective rooting depth of winter wheat and fixing N for its own growth and for the subsequent winter wheat crop (Rao et al., 2002a,b).

2.2.3. Cover crops as forage in the Northeast and Midwest U.S.

In the cool, humid region of the Northeast and Midwest regions (Fig. 1), best opportunities for planting cover crops for forage have been after harvesting winter wheat for grain (mid-summer), corn for silage (late summer to early autumn), and soybean for grain (early autumn). As well, cover crops can be planted after harvesting short-season crops such as potato (*Solanum tuberosum* L.) and various high-value vegetable crops (mid-summer), but much less land is devoted to those crops. Planting cover crops from mid-summer to early autumn usually provides sufficient growth of forage to support grazing by late autumn and early winter, depending on location and rainfall. Planting winter-hardy cover crops in late summer or early autumn can also provide forage in the spring. Late planting (e.g., after soybean or corn grain harvest) in northern locations typically does not provide enough time to accumulate sufficient biomass to support grazing animals prior to the onset of winter, so it is best to plant winter hardy species that can be grazed in early spring. The best winter-hardy species to use are winter rye, winter wheat, and winter triticale (×*Triticosecale* Wittmack). Winter wheat and rye were effective as double-crop forage in corn-soybean cropping systems in Michigan when they preceded soybean in the rotation (Thelen and Leep, 2002). In Nebraska, winter rye was considered the most winter hardy and versatile of several cover crop species evaluated in an integrated crop–livestock system (Lesoing et al., 1997). Rye growth was sufficient to carry 2.7 cows ha^{-1} for 30 days during spring grazing. Other short-season cover crop species with potential to produce forage include annual ryegrass and *Brassica* spp. (Fae et al., 2009; Kallenbach et al., 2003; Penrose et al., 1996; Reid et al., 1994). There is increasing interest in planting cover crops for forage after corn silage harvest, but establishment of cereal grains, annual ryegrass, and *Brassica* spp. is more consistently successful when seeded in early to mid-August after winter wheat grain harvest. A survey of New York dairy farms showed that cover crops were planted primarily for soil conservation, to increase soil organic matter, and for manure nutrient management; however, a significant percentage of farmers indicated they also harvest their cover crops for forage or grain (Long et al., 2013).

Cereal species and mixtures can be selected to provide high quality forage primarily in late autumn, early spring, or in both the autumn and spring, depending on planting date (Maloney et al., 1999; McCormick et al., 2006). Oat sown in early August in Wisconsin after winter wheat grain harvest produced 6700 kg ha^{-1} of dry matter with neutral detergent fiber of 521 g kg^{-1} and crude protein of 180 g kg^{-1} when harvested 77 days after planting (Contreras-Govea and Albrecht, 2006). In a two year study in Ohio, rye + oat that was no-till planted in early September after corn silage produced 2370–3990 kg ha^{-1} dry matter by late November and 2400–4350 kg ha^{-1} in early spring with neutral detergent fiber of 390 g kg^{-1} and *in vitro* neutral detergent fiber digestibility of 837 g kg^{-1} (Fae et al., 2009). Oat produced most of the forage growth in autumn, whereas winter rye produced all the forage in spring, because freezing temperature during the winter killed the non-winter hardy oat. Forage grazed by Holstein and Jersey heifers provided average daily gain of 0.76 kg day^{-1} and one animal unit (455 kg) grazing for 172 days ha^{-1}.

In an integrated crop-livestock system in Illinois, grazing of cover crops increased soil penetration resistance, however soil aggregate stability in water was greater, corn grain yield was 6% greater, and soil organic C increased with time compared with continuous corn cropping without grazing (Maughan et al., 2009; Tracy and Zhang, 2008). Weed biomass and weed species composition were little affected by grazing, but crop rotation and use of annual cover crops in the integrated system appeared to be primary drivers in suppressing weed biomass and changes in weed species composition (Tracy and Davis, 2009). Integration of crops and cattle had generally positive effects on crop yield, and therefore, the authors concluded wider adoption of integrated crop-livestock systems could reduce reliance on herbicides and improve soil properties compared with conventional grain cropping systems in the Midwest U.S.

In the Pacific Northwest, cover crops are being used as a sustainable strategy to reduce soil erosion, build soil organic matter and surface structure, and reduce requirements for fertilizer N, particularly in organic management systems. By planting cover crops earlier in the autumn (mid-September compared with early October), an additional 144–167 growing degree days (>4 °C) were accumulated, which fostered an additional 1300–1900 kg ha^{-1} of cover crop biomass (Lawson et al., 2013). Removal of hairy vetch cover crop biomass as forage led to greater soil N availability than in the no-cover crop control or in rye and ryegrass cover crops (Kuo and Jellum, 2002). Corn grain yield was attained with nearly equal levels of N fertilizer, regardless of whether cover crops were removed as forage or not. These results demonstrate the positive opportunities for integration of crops and ruminant livestock in the region.

2.3. Crop residue grazing

Allowing livestock to graze crop residues remaining after grain harvest is one of the simplest and most economical methods to integrate livestock into grain crop rotations. Crop residues represent a vast feed resource available to ruminant livestock producers and offer opportunities for significant reduction in winter feed costs (Lawrence and Strohbehn, 1999). This practice has been widely adopted on farms where beef cattle are present in the western Midwest and east-central Great Plains region, such as Iowa, Kansas, and Nebraska. For example, corn residue can supply 100–150 days ha^{-1} of grazing for one animal unit (455 kg) under favorable weather conditions. Grazing crop residues reduces soil surface cover by 5–25% (Clark et al., 2004; Lesoing et al., 1996), so erosion control may not be compromised. Grazing, rather than mechanical harvesting has been the most economical method of utilizing corn residue in beef cow systems, however some producers in proximity to ethanol plants have been baling corn residue and blending it with wet or dry distiller grains to replace hay fed to cattle.

Soil compaction resulting from winter grazing of cover crops and crop residues is often a concern voiced by producers who have not adopted this practice. It is possible for animal grazing to have large detrimental effects on subsequent crop production and on the soil environment if not managed properly. Research has demonstrated that soil compaction by animals and associated soil disturbances are minimized under the following conditions when grazing crop residues: (i) grazing is restricted to periods when soils are dry or frozen, (ii) in colder regions, multiple freeze-thaw cycles during the winter alleviate surface compaction, (iii) soils containing high surface organic matter buffer the impact of cattle traffic, and (iv) soil is appropriately tilled before planting a cash crop (Clark et al., 2004; Liebig et al., 2011b; Maughan et al., 2009). Soil compaction from crop residue grazing is less of a concern in the west, because dry or frozen soil conditions are more likely during grazing periods than in eastern regions of the U.S.

In the northern Great Plains, cows are typically wintered in a feedlot and fed hay baled during the previous summer. Hay is one of the most expensive methods of feeding forage, and cows are often fed hay during a period of time when their nutritional requirements are lowest. Snowfall in northern regions interferes with grazing of crop residues and stockpiled forage (via deferred grazing practices). To solve this problem, Tanaka et al. (2005) demonstrated the feasibility of integrating crops and livestock by mechanically swathing forage and crop residues in windrows that are grazed by cattle during the winter, while harvested grain could be marketed off-farm or fed to livestock on the farm (i.e. marketed indirectly). Purchased inputs such as fertilizer and pesticides were minimized by adding legumes to the rotation. The 3-year cropping system provided greater crop diversity as well as crop residues and forage with sufficient quality to meet the nutritional requirement of dry-pregnant cows. Wintering dry-pregnant beef cows on swathed forages and crop residues reduced winter feeding costs by about 33% when compared with cows fed baled native hay in a feedlot (Karn et al., 2005). The authors concluded that crop and livestock performance were not jeopardized, while long-term impacts could become synergistic for both enterprises. Thus, even in northern climates, it is possible to introduce greater diversification in cropping systems via the integration of livestock grazing on swathed crop residues and forages.

2.4. Sod intercropping

Sod intercropping is the practice of establishing a crop into a perennial forage stand (i.e. sod), which may be temporarily or permanently suppressed using various means. The warm, humid region of the southeastern U.S. (Fig. 2) offers climatic advantages for using annual crops in rotation with suppressed perennial forages (Franzluebbers, 2007). Beef producers in the region often overseed seasonally dormant warm-season bermudagrass with annual grasses (e.g. annual ryegrass, rye) and/or legumes such as crimson clover in autumn to increase forage supplies during the cooler months of the year. Sod intercropping can also occur by planting winter cereals for grain production in winter-dormant bermudagrass hay fields. Likewise, summer cash crops can be interseeded into perennial cool-season forages, such as tall fescue [*Lolium arundinaceum* (Schreb.) Darbyshire]. The use of herbicide-resistant crop varieties (available in corn, cotton, soybean) and improved no-till planting technologies can facilitate the success of this practice. Franzluebbers (2007) reviewed the literature on corn grown for grain when interseeded into suppressed tall fescue, and concluded that a multitude of opportunities are possible for producers, depending on availability of supplemental irrigation and their need to balance grain and forage production.

Some species used as living mulches can also be utilized to produce forage in rotation with annual grain crops, but adoption of such a system is virtually nonexistent because of managerial difficulty and several studies showing reduced corn yield due to competition for water, light, and nutrients (Sulc and Tracy, 2007). Recent investigations in the upper Midwest have demonstrated more promising results using established perennial kura clover (*Trifolium ambiguum* M. Bieb.) that is normally used for forage production, but can be temporarily suppressed with herbicides for planting to corn for one year (Zemenchik et al., 2000). Little or no reduction was observed in whole-plant or grain yield of corn grown for one year in the suppressed kura clover sod and the system appeared to be largely self-sufficient in N availability. After one year of corn grown for grain or silage, suppressed kura clover sod was allowed to recover and reached full forage production within 12 months. Herbicide-resistant corn technology improved the consistency in managing kura clover as a living mulch for corn production (Affeldt et al., 2004). Such a system may be more attractive to producers who are reluctant to destroy a productive perennial pasture sod in exchange for rotational benefits to a grain crop. The opportunity to economically renovate declining pastures also may be possible with this kura clover sod suppression scheme when used within integrated crop-livestock systems. Evaluation of this system is needed in other locations, because irrigation may be required for consistent success where summers are warmer and drier than where it has been tested.

2.5. Dual-purpose cereal crops

Cereal grains (e.g. rye, wheat) have commonly been used for high-quality pasture from late autumn to early spring in southern Great Plains states (Fig. 1), especially Oklahoma and Kansas. Cereal grains can be grown exclusively for pasture, or for dual-purpose forage and grain production. Stocking rates vary from 280 to 560 kg live animal ha^{-1} in late autumn to winter and from 560 to 1100 kg live animal ha^{-1} in the spring. In Oklahoma, beef steers gained 0.96 kg $head^{-1}$ day^{-1} on winter wheat pasture stocked at 1.2 head ha^{-1} for 84–115 days (Horn et al., 1995). Tall winter wheat cultivars often had greater grain yield when grazed until the jointing stage compared with no grazing, but grazing of semi-dwarf cultivars should cease at an earlier stage to avoid grain yield reductions (Redmon et al., 1995). While dual-purpose wheat production is most common in the southern Great Plains, studies have demonstrated potential for this practice further north (Islam et al., 2013; Lyon et al., 2001).

There are potential negative production and environmental effects of grazing wheat prior to reproductive development if not managed carefully. Animal trampling can deteriorate soil physical properties and reduce root growth and yield of subsequent wheat crops on conventionally tilled soils with low surface soil organic matter (Krenzer et al., 1989; Worrell et al., 1992). However, stocking pressure and amount of residue left is an important management tool in limiting the negative effects of grazing animals. For example, when winter wheat residues were maintained at 3500 kg ha^{-1} after termination of grazing, subsequent grain sorghum yield in a no-tillage crop rotation was similar to grain yield in the non-grazed treatment (Winter and Unger, 2001). Another study demonstrated the potential for increasing overall productivity of a dry land wheat-sorghum-fallow rotation by using limited grazing of the wheat and sorghum stover with no significant reduction in subsequent grain yields (Baumhardt et al., 2009).

2.6. Agroforestry and silvopasture

Agroforestry offers great potential for increasing system productivity through intentional integration of trees, forages, and livestock (Fike et al., 2004). Spatial arrangement can be designed to optimize benefits on (i) timber or nut production, (ii) forage quality and livestock performance, (iii) crop production, (iv) erosion protection, C sequestration, and water quality, (v) wildlife habitat and biodiversity protection, and (vi) economic opportunities. With wide tree spacing, annual crops such as corn or soybean can be grown and generate income when trees are too small for grazing animals to be present. An agroforestry system developed in Mississippi used cattle to graze corn rather than harvesting for grain by machine (Glover Triplett, personal communication, 2007). Initial observations indicated that tree growth was accelerated by fertilizer applied to the corn, which could shorten the time for trees to

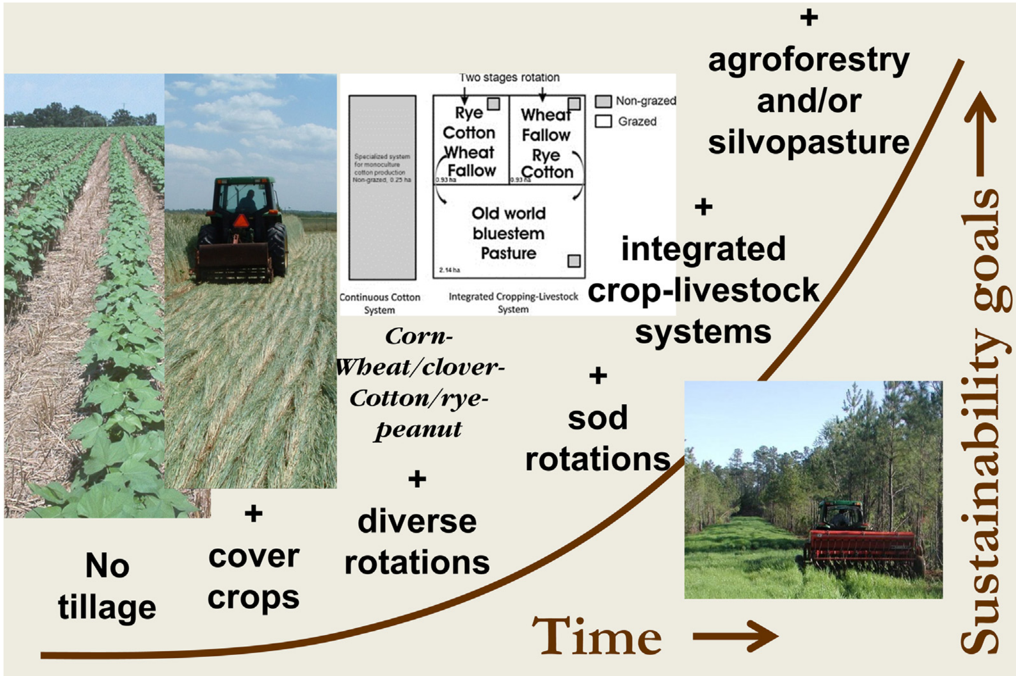

Fig. 3. Schematic diagram projecting attainment of sustainability with time by increasing complexity of cropping systems.

mature enough to convert to silvopasture and eventually for timber harvest. With increasing maturity of trees, perennial forages become better suited as a profitable herbaceous understory. A replicated research and demonstration project in the Coastal Plain of North Carolina was managed for crop production during tree establishment (Cubbage et al., 2012) and will eventually be converted to silvopasture production (Paul Mueller, personal communication, 2013).

Trees integrated with pasture may improve nutrient retention and increase soil organic C compared with treeless pastures and conventional cropping. In Florida, Nair et al. (2007) reported that integrating trees and pasture enhanced nutrient retention, thus reducing the likelihood for nutrient transport to surface water when compared with treeless pastures. Soil organic C was generally greater under agroforestry than under conventional cropping (Kumar and Nair, 2011). However, there is still large uncertainty in estimating or modeling C dynamics in agroforestry systems due to large in-field variability, measurement expense, and several factors related to soil C sampling (Nair, 2011b).

Silvopasture is practiced in pine plantations of the southeastern U.S. and coniferous forestlands in western regions. Research is ongoing in other regions, primarily in the Midwest and in the state of Virginia, but expansion of this practice is hampered by lack of producer knowledge and decision support systems for implementation (Fike et al., 2004). Interaction among trees, forage, and livestock adds significant managerial complexity. Adoption is also curtailed by the necessity and cost of adding fencing and water systems to forested lands, unless the system is developed by planting trees to existing pastures that already have water and fencing systems present. That approach requires careful management and additional fencing to ensure seedling trees are protected until they are large enough to withstand livestock grazing.

3. Outlook for integrated crop-livestock systems in the U.S.

Opportunities abound in the U.S. for achieving greater integration of crop and livestock systems. Although specialized agricultural systems are the norm in the U.S. due to various influences of ownership, markets, state and federal policies, regulations, and knowledge institutions, recognition of the need to balance production with environmental and social goals is becoming increasingly clear (NRC, 2010). Specialized crop producers have generally shown little interest in integrated crop-livestock systems due to comfort with commodity support policies, managerial ease of crop only systems, and rising market prices for their products that preclude any felt need to consider additional enterprises or alternative production systems. Most crop producers are not eager to take on the additional managerial complexity involved with diversified, integrated-crop livestock systems. Rapid growth in corn ethanol production, high demand for corn and soybean grain, and high grain prices in the U.S. will most likely curtail immediate pursuit of farm diversification by crop farmers. In contrast, producers who predominantly feed livestock on their farms have been more interested in integrating cash crops with cow-calf or stocker cattle operations, if their land resource is suitable for cash crop production. Rising input costs could be a significant driver for greater crop-livestock integration as a means to diversify revenue.

Expansion of sod-based crop rotations might occur throughout the eastern U.S. with development of cellulosic biofuel production systems as a significant incentive to change practices. A reasonable projection might be for native perennial grasses [e.g. switchgrass (*Panicum virgatum* L.) alone or in combination with other native, warm-season perennials such as Indiangrass (*Sorghastrum nutans* (L.) Nash), eastern gamagrass (*Tripsacum dactyloides* L.), little bluestem (*Schizachyrium scoparium* (Michx.) Nash), and big bluestem (*Andropogon gerardii* Vitman)] to be harvested for cellulosic biofuel production, alternated with ruminant livestock grazing and application of additional livestock manure for several years, followed by several years of cash grain and fiber crops such as corn, soybean, wheat, peanut, and cotton using conservation tillage and livestock grazing of cover crops in the winter. Such a system could potentially increase soil organic matter and preserve soil quality so that improvements of water quality and reductions in greenhouse gases can be simultaneously achieved. It could be implemented on whole fields or along sensitive corridors in the landscape to achieve water quality and biodiversity objectives (Asbjornsen et al., 2013).

Land having cover crops as high-quality forage for ruminant livestock might also expand throughout the eastern U.S., although more immediate implementation could be expected in the southeastern U.S. due to the long growing season and more favorable climatic conditions for double cropping. As a progression of adoption of conservation agricultural systems, moving more farmers to adopt the practice of planting a cover crop for erosion control in conservation-tillage management systems will be a reasonable first step (Fig. 3). With familiarity of planting and terminating cover crops in their operation, a logical next step will be to utilize the cover crop as forage that is either mechanically harvested or grazed directly by livestock. For example, a survey of dairy farmers in New York showed the potential for increasing adoption of winter cereals as commodity cover crops, harvested for forage, among those who are already growing cover crops (Long et al., 2013). How the cover crop is chosen, cultured, and utilized are researchable topics, but developing more robust production systems with actively growing roots whenever possible will lead to improved soil and environmental quality.

Assuming future adoption of sod-based crop rotations and grazed cover crops, there will be increasingly greater opportunities in the landscape for grazing of crop residues throughout the eastern U.S. and expansion of dual-purpose winter wheat production outside the Southern Plains region. In the eastern U.S., particularly east and south of the Midwest region, smaller and irregularly shaped fields with sloping land surfaces may create opportunities for developing integrated crop-livestock systems along with agroforestry and/or silvopasture arrangements. Various tree species are possible, some for timber, some for wildlife habitat, and some for fruit and nut production. Much basic research remains to be conducted in agroforestry and silvopasture systems (Nair, 2011a), but the benefits to crop and animal production, above-ground and below-ground biodiversity, and soil, water, and air quality may soon be more recognized and promoted in government incentives and policies (USDA, 2011).

Several technologies have greatly improved opportunities for producers to develop successful integrated crop-livestock systems. These include conservation tillage, improved weed control practices, fertilization, improved plant genetics, and planting technologies (Franzluebbers, 2007). For example, combinations of conservation tillage, improved no-till planters, herbicide-resistant and insect-resistant plant varieties, and greater reliance on ecological strategies to control competition for light, nutrients, physical space, and water are improving the success of establishing annual crops into living, partially killed, or completely killed annual cover crops or perennial sods. Conservation tillage management will be especially useful in developing ecologically responsible integrated crop-livestock systems, because it enhances soil conservation, and from a practical standpoint, facilitates diversification of cropping systems by reducing expenses and time required for seedbed preparation between multiple crops (Franzluebbers, 2007). No-tillage practices also reduce the impact of animal traffic on cropland (e.g. when grazing winter cover crops) by maintaining soil structure during establishment of cover crops or other short-duration forage crops in more complex rotations. Portable electric fencing and improved water systems can also contribute to the ease of incorporating livestock on croplands or in silvopastures where permanent fencing is not present, such as may occur when grazing crop residues, cover crops, or dual-purpose cereal grains. Although more research is needed to develop crop species and varieties specifically designed for integrated systems, genetic selection has already improved the productivity of many short-season crops that can serve as components of integrated-crop livestock systems, including annual ryegrasses, brassicas, clovers, sorghum species, peas, and others.

As Russelle et al. (2007) pointed out, the diminishing contribution of agriculture to the Gross Domestic Product (<1% in 2000 compared with 8% in 1930) and the general availability of food to most U.S. citizens have seemingly marginalized agriculture's importance to the public and policymakers, at least in terms of funding research and development of more sustainable agricultural approaches. Current agricultural research, education, and extension efforts in the U.S. are not sufficient to develop and implement more sustainable agricultural systems requiring greater managerial complexity in the face of more expensive and insecure fossil-fuel supplies, changing and less predictable climate, increasing need for global food production, and increasingly serious limits to water quality and quantity. Changes in agricultural policy will be needed to bring about greater adoption of integrated agricultural systems to achieve more robust ecosystem services from agricultural land. The ecological complexity of integrated crop-livestock systems and their potential to achieve desirable ecosystem services (e.g. food and fiber production, air quality and climate regulation, maintenance of soil and water quality, cycling of water and nutrients, and preservation of biodiversity) justify national and international investments in research and education collaborations to overcome barriers to adoption of these sustainable agricultural systems.

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